Fuel Flow and Stock during Deuterium-Deuterium Start-up of Fusion Reactor

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1. Background

Flow and stock of fusion fuels in a fusion reactor has been investigated from the aspect of system-dynamics. In particular, operational scenario of the start-up only by deuterium (D) has been discussed including effects of dilution due to helium (He) ash and fuel recycling in a plasma vacuum vessel. Initial loading of tritium (T) in a fusion reactor is a critical issue because of availability of T. Thus, the start-up only from D has been attracting interests. The present model of burning plasma has been much improved compared with the previous research which showed technical feasibility of this D-D start-up scenario [1]. The temporal evolution of plasma temperature has been solved in an integrated manner of temperature and density profiles, an empirical scaling of energy confinement time, isotope effect of confinement, slowing down and velocity distribution function of energetic particles, dilution due to He ash, radiation losses, and recycling of fuels. Operational parameters are based upon the recent tokamak fusion DEMO design by the Joint Special Design Team in Japan [2] with nominal fusion power of 1.4GW.

2. Model

The shape of Temperature profile and density profile is given by model function below.

$$n(\rho) = (n_0 - n_b)(1-\rho^2)^{0.6} + n_b$$

$$T(\rho) = (T_0 - T_b)(1-\rho^{1.5}) + T_b$$

where n_0 and T_0 are central Value, n_b and T_b are boundary value, and $n_b = \frac{1}{1.3} n_0$, $T_0 = 3\text{keV}$. Profile function is represented with finite number of shells. A temperature of each shell is calculated to satisfy the following relationship

$$W_p = T_i * 3kV_{p_i} n_i$$

where V_{p_i} is the plasma volume of a shell (m^3), n_i is the electron density of a shell, T_i is the temperature of a shell, and W_p is the plasma thermal energy (MJ).

W_p and accumulation of tritium are calculated using the idea of stock and flow of a system dynamics model. In the model, inflows to the W_p are the alpha heating and NBI heating of 61.9MW; outflows are bremsstrahlung radiation, cyclotron radiation, and the loss due to energy confinement. For energy confinement time, the ITER-98P(y,2) scaling has been used [3],

$$\tau_E = 0.0562 I_p^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78}$$

, where I_p, B, P, n, M, R, ε and κ_a are plasma current in MA, magnetic field in T, density in 10^{19}m^{-3}, mass number of fuel ions (AMU), major radius in m, inverse aspect ratio and elongation, respectively. The mass number is traced by $(2n_D+3n_T)/n_e$, where n_e is fixed at $5.27\times10^{19}\text{m}^{-3}$. Fusion cross sections are calculated by polynomial approximation based upon the well-used model [4].

Helium dilution is integrated with formulation of deuterium density using charge neutrality below

$$n_\text{D} = n_e - n_T - 2 * n_{He}$$

where values of n_T and n_{He} are calculated from number of fusion reactions.

3. Result

In the case without He dilution and recycling, it takes 105 days to reach the DT fuel equilibrium in a burning plasma and 481 days to save T storage of 5 kg which is required for initial loading of a DT fusion reactor. Here tritium breeding ratio (TBR) is assumed to be 1.1. When TBR is degraded to 1.05, T storage is only 1.6 kg after 481-days operation. Impact of fuel dilution due to He ash in this scenario is serious. When equivalent particle confinement is assumed for He and T, fusion power is degraded to 0.74GW and T storage is 2.4 kg after 481-days operation.

References

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